

THE PATHFINDER MISSION TO MARS

Autonomous Navigation and the Sojourner Microrover

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The Mars exploration program has as an overarching theme the search for and understanding of life, climate, and resources on this fascinating planet. The ability to move about the surface of Mars is key to making measurements and the gathering of the data which address this theme (1). In October 1992, the NASA Office of Space Access and Technology funded an experiment to demonstrate the mobile vehicle technologies needed for a Mars surface mission (2). That experiment, the Microrover Flight Experiment (MFEX) or "Sojourner," flew on the Mars Pathfinder (MPF) mission, which began on 4 July 1997 and ended 26 September 1997.

During the 83 sols (1 sol = 1 martian day = 24 hours, 40 min) of the Mars Pathfinder mission, the MFEX rover was released from the Mars Pathfinder lander and performed its mission to conduct technology experiments such as determining the interaction between martian soil and the rover wheels; navigating, traversing, and avoiding hazards; and gathering data on the engineering capability of the vehicle (thermal control, power generation performance, communication, and so forth). In addition, the rover carried an alpha proton x-ray spectrometer (APXS), which allowed researchers to determine the composition of soil and rock. Lastly, a great amount of engineering data was obtained from images of the lander taken by the rover; this was particularly helpful in assessing status of the mission and damage to components.

The MFEX rover (Fig. 1) activities were directed by an operations team on Earth. This team, working under the constraints of limited lander power and restricted antenna coverage at Earth, could (once per sol) command the rover to drive, take pictures, perform experiments, and collect and transmit data to the lander. The rover was required to carry out these tasks safely without intervention from the operations team until the next command opportunity on the next sol. In so doing,

the rover used techniques for autonomous control which were (among several technologies) first demonstrated in flight on this mission. One such technique for autonomous navigation and hazard avoidance

is briefly described below (3, 4, 5).

The "Go to Waypoint" command was the primary implementation of autonomous navigation on the MFEX rover. This command was issued by the member of the operations team called the "rover driver." The driver used rover camera images, lander stereo camera images taken of the rover in the terrain, and portions of a stereo terrain panorama to identify the rover location and the site of interest (the goal location of the "Go to Waypoint" command). Through a graphic overlay system used with the stereo images, the driver specified the x and y coordinates of the rover location and the new target. These coordinates were in a coordinate frame (the "surface-fixed frame") that became fixed to

the surface of Mars at the time the MPF lander completed sun-finding and identified the direction of martian north on sol 1. Intermediate waypoints (as needed) were also defined by the driver if there was a preferential path toward the final destination (such as a route to avoid obvious hazards along the path). If the rover was not already facing the next waypoint, it was commanded to turn toward the goal, until it faced the destination. These commands ("Go to Waypoint," turns, and a command to update the position of the rover in the x and y coordinate frame) were sent to the rover as part of a single command sequence.

Upon execution of the "Go to Waypoint" command, the rover drove an approximate straight line, adjusting its path when it detected drift off its course or encountered a hazard condition. During execution of a "Go to Waypoint" command, the rover updated its position relative to the lander to determine (at a minimum) if it had reached the objective of the traverse. This position relative to the lander was kept in the same x and y coordinate system as the commands developed by the rover driver back on Earth. The update to position was performed by a form of dead reckoning. Encoder counts were accumulated on each of the wheel actuators, where a single encoder count was registered each time the motor shaft of the actuator completed a revolution. The accumulated counts on each of the six wheels were averaged to determine the number of motor revolutions executed. Given the gearing ratio of 2000:1, encoder counts were turned into wheel revolutions and thus distance traveled. During turns, the rover measured the change in orientation by integrating the output from an onboard rate gyro. Distance and angle were then used to compute an x and y location.

The rover could autonomously identify several types of hazards. Among these were proximity-detected rocks, drop-offs, slopes, excessive tilt of the vehicle, a triggered contact sensor, or a combination thereof. If the rover detected a proximity hazard, the vehicle turned in place in increments, until the hazard was no longer detectable. Then the vehicle drove forward one-half vehicle length, after which it resumed normal traverse operations, heading back toward the goal location. At this point, the rover maintained no memory of the hazard that it had just avoided.

Proximity hazard detection was performed with the forward cameras and five laser strip-

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ers. Every 7 cm of traverse, the rover stopped and executed a sensing cycle. The rover captured an image both with and without a laser active. Selected scan lines from each image were differenced to locate the laser spot in the scene. (Fig. 2 shows the infrared laser stripe, as seen by the rover during surface operations) If the terrain is flat and level, as referenced from the rover, the laser spot was visible in a known position along the scan line. Deviations from flat and level ground would cause the laser spot to slide along the scan line, indicating a rock or depression. If the spot could not be found in the difference image, a significant drop-off may exist. Repeating this process for five lasers and four sets of scan lines per difference image generated a set of 20 terrain height measurements. Height differences between adjacent measurements could indicate a rock or hole; sufficient height difference between the lowest and highest measurements in the set indicated a steep slope or drop-off. False hazard detections could occur if the camera view of a laser spot was blocked by a craggy surface; so ignoring a small number of data drop-outs was possible by modifying parameter settings in appropriate terrains. During operations on Mars, the rover was commonly directed to accept up to three data drop-outs before avoiding the drop-outs as a hazard.

The geometry of the laser stripes was arranged so that obstacles could be detected to the sides of the rover traverse direction at sufficient range so that the entire rover's turning circle (a circle 70 cm in diameter) was free of hazards. This allowed the rover to turn around in place and drive forward to avoid an obstacle. If the density of hazards in the terrain was too high to permit the vehicle to maintain a clear turning circle, a "thread the needle" approach could be enabled. This technique permitted the rover to drive between obstacles that were apart at least one vehicle's width. If enabled, the rover would attempt to drive in a straight line along the perpendicular bisector between the two obstacles. It would continue driving until it found a clearing large enough to turn around in before a specified distance was elapsed. If no such clearing was detected, it backed straight out to the point at which the "thread the needle" was initiated. Another direction for driving would then be attempted.

Excessive tilts were measured with on-board accelerometers (one aligned to each axis of the vehicle). These accelerometers served as a set of inclinometers, measuring

the angle to the local gravity vector. An angle measurement beyond a threshold (not greater than a 30° slope) represented an excessive

slope condition. When this was encountered, the rover would turn away from the excessive slope, traverse beyond the hazard, then turn back in the direction of its destination.

Contact sensors provided the hazard detection system of last resort [JM1] for the rover. Sensors were located on bumpers on the front and rear of the rover solar panel, and on the lower front body of the rover. Additional contact sensors were incorporated into the APXS deployment mechanism, located at the rear of the rover. If an obstacle in the rover's path was not detected by the proximity hazard detection system, the triggering of any of the bumper contact sensors would either abort the traverse or cause the rover to back up, turn, and avoid the hazard.

If a specified waypoint destination was not reached within the time allotted for the execution of the command, the traverse would end and an error "flag" was set in the command sequence [JM2]. The error flag prevented the rover from continuing unproductive attempts to achieve an unreachable goal. Depending on the parameter settings in the sequence, any remaining traverse commands were skipped (because the rover was not where it was expected) or the rover continued on to the next specified location.

The autonomous navigation performance of the rover on Mars generally equaled or exceeded the performance observed during tests on Earth. Because of the nearly obstacle-free nature of the terrain in the immediate vicinity of the lander, initial rover traverses were commanded through low-level moves, with no "Go to Waypoint" commands used. By sol 12, once the laser/camera hazard detection system was calibrated (an example of a measurement is shown in Fig. 2), the first "Go to Waypoint" command was executed. Consistent with earlier ground testing, position error was roughly 5 to 10% of distance traveled. (The average rover traverse during the mission was about 2 to 3 m/sol)

The average drift of the heading reference subsystem was approximately 13° per sol of traverse. The result of this dead reckoning performance was that autonomous traverses through the "Go to Waypoint" commands did

not always lead the rover to the expected location. However, the hazard detection system worked well, successfully keeping the vehicle away from nontraversable hazards.

Although some of the observed difficulties were clearly due to limitations in the implementation of autonomous navigation on board the vehicle, the performance can also be attributed to the caution of the operation team in enabling the rover's full suite of hazard avoidance features during specific traverses. This caution was understandable, given that each rover traverse inherently put the vehicle at risk of a premature end of the mission.

In future planned rover missions, such as the Mars Surveyor Program 2001 mission, the operations team will not be able to meet the mission objectives while maintaining a cautious approach to autonomous navigation. In these missions, the rover will be required to traverse approximately 100 m/sol in order to reach sites of scientific interest and collect samples for eventual return to Earth. This is equivalent to performing all of the traverses of the MEX rover during the entire Pathfinder surface mission in a single sol. Such long-distance traverses will require a significant increase in autonomous capability. Under consideration for this future mission are onboard techniques for terrain feature tracking, creation of obstacle maps, and visual tracking to targets which may aid mission performance through improvements in autonomous navigation.

References and Notes

1. D. Shirley and J. Matilevic, *Mars Rovers: Past, Present and Future*, Princeton Space Studies Institute 20th Anniversary Conference, Princeton, NJ, May 10, 1997 (Publisher, location, 1997) [JM3].
2. J. Matilevic and D. Shirley, *Control Eng. Practice*, 5, 827 (1997).
3. E. Gat, R. Dezel, R. Miv, J. Loch, D. Miller, *IEEE Trans. Robotics Autom.* [JM4] 10, 490 (1994).
4. R. Brooks, *IEEE J. Robotics Autom.* RA-2, XXX (1986) [DV5].
5. B. Wilcox, D. Gennery, A. Mishkin, *Proc. SPIE* 1007, XXX [JM6] 1988.
6. This work was carried out by the Jet Propulsion Laboratory, California Institute of Technology under a contract with NASA.

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Fig. 1 The MEX rover.

Fig. 2. Image of laser stripe from front left rover camera.

Page: 2

[JM1]Is there a need for quotation marks around this phrase? (i.e. ...system "of last resort" for the...)

Page: 2

[JM2]As meant?

Page: 2

[JM3]Please provide publisher and location for this conference. Princeton, NJ, is correct?

Page: 2

[JM4]My sources indicate that this journal was *IEEE J. Robotics Autom.* until 1988, when it became *IEEE Trans. Robotics Autom.*

Page: 2

[DV5]Please supply page number for this citation.

Page: 2

[JM6]This is a regular journal; list simply as: volume, starting page (year).

Corrections:

- last sentence, paragraph 2, first column, page 1, lines 44-49

please make this read:

Lastly, images of the lander taken by the rover were particularly helpful in assessing status of the mission and damage to components.

- editor's comment, JM1, first sentence, paragraph 2, second column, page 2, line 21, "of last resort".

No need for quotation marks. They may be removed as shown in the proof.

- editor's comment, JM2, first sentence, paragraph 3, second column, page 2, lines 36-37

please make this read:

and an error "flag" was set in the on-board command execution software. This error flag prevented...

- editor's comment, JM3, References and Notes, item 1

Yes. Princeton, NJ is the correct location

- editor's comment, JM4, References and Notes, item 3

You are correct. My mistake.

- editor's comment, DV5, References and Notes, item 4

I am unable to supply page numbers for this reference.

- editor's comment, JM6, References and Notes, item 5

This paper appeared in a conference proceedings, not in the journal Optical Engineering. Please retain reference as originally submitted:

B. Wilcox, D. Gennery and A. Mishkin, "Mars rover local navigation and hazard avoidance", Proc. SPIE Conf. 1007, Mobile Robots III, November 1988.

Autonomous Navigation and Hazard Avoidance Technology of the Mars Pathfinder Microrover ("Sojourner")

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The Mars exploration program has as an overarching theme the understanding of life, climate and resources on Mars. The ability to move about the surface of Mars is key to making measurements and the gathering of the data which address this theme. In October, 1992 the NASA Office of Space Access and Technology funded an experiment to demonstrate the mobile vehicle technologies needed for a Mars surface mission. That experiment, the Microrover Flight Experiment (MFEX) or "Sojourner", flew on the Mars Pathfinder mission, which began on July 4, 1997 and ended September 26, 1997.

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The MFEX rover (see Figure 1) performed this mission as directed by an operations team on Earth which through a once per sol opportunity, commanded the rover to drive, take pictures, perform experiments, collect and transmit data to the lander. The rover was required to carry out these tasks safely without intervention from the operations team until the next command opportunity. In so doing, the rover used techniques for autonomous control which were (among several technologies) first demonstrated in flight on this mission. One such technique, for autonomous navigation and hazard avoidance, is briefly described below.

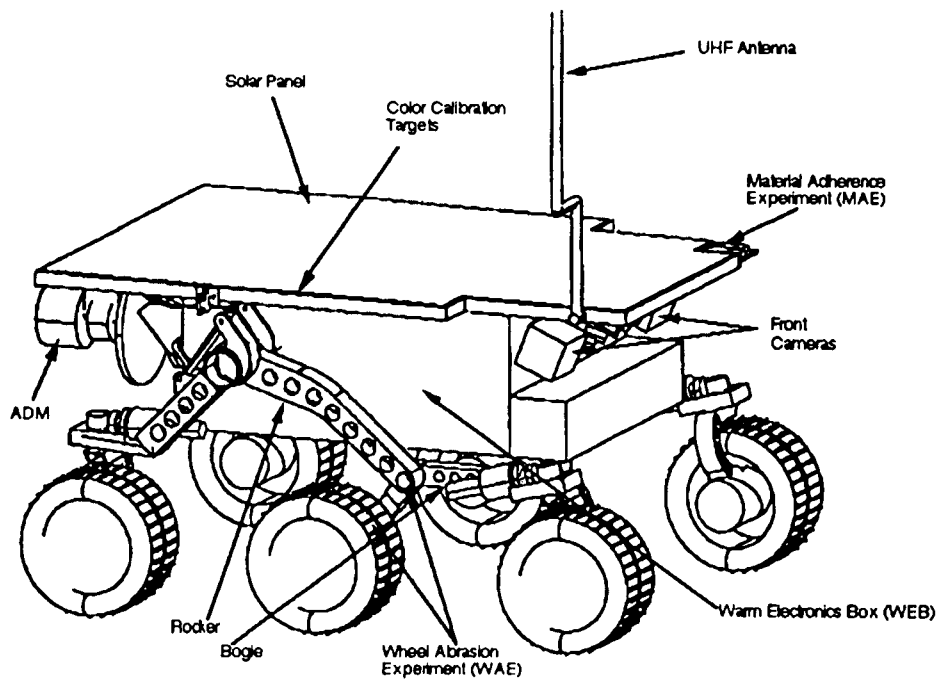
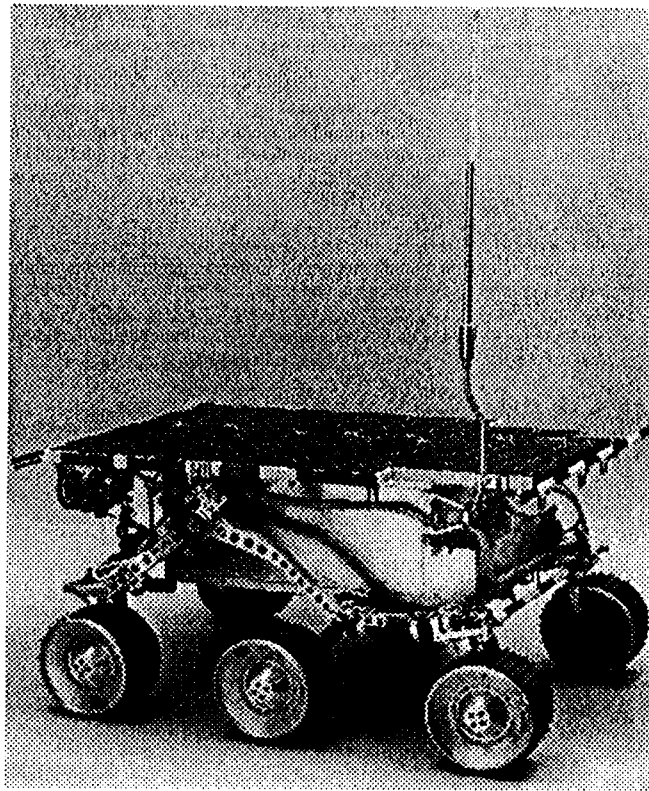


Figure 1. The MFEX rover

The "Go to Waypoint" command was the primary implementation of autonomous navigation on the MFEX rover. This command was developed by the member of the operations team called the 'rover driver'. The driver, using rover camera images, lander stereo camera images taken of the rover in the terrain, and portions of a stereo terrain panorama, identified the rover location and the site of interest (the goal location of the "Go to Waypoint" command). Through a graphic overlay system used with the stereo images, the driver specified the x,y coordinates of the rover location and the location of the goal of the command. These coordinates were in a coordinate frame (the "surface-fixed frame") that became fixed to the surface of Mars at the time the MPF lander completed sun-finding and identified the direction of Martian north on sol 1. Intermediate waypoints (as needed) were also defined by the driver if there was a preferential path toward the final destination (e.g., directing the rover to avoid obvious hazards along the path). If the rover was not already facing the next waypoint, it was commanded to turn toward the goal, until it faced the destination. These commands ("Go to Waypoint", turns and a command to update the position of the rover in the x,y coordinate frame) were sent to the rover as part of a single command sequence.

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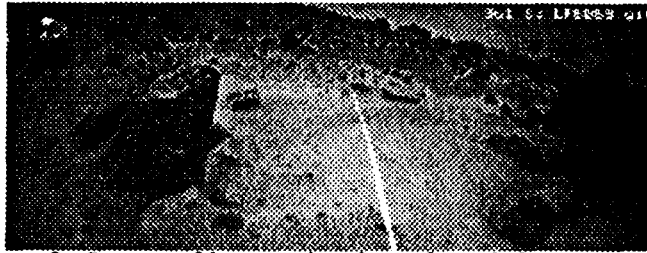


Figure 2. Image of laser stripe from front left rover camera

The geometry of the laser stripes was arranged so that obstacles can be detected to the sides of the rover traverse direction at sufficient range so that the entire rover's turning circle (a circle of diameter 70cm) was free of hazards. This allowed the rover to turn around in place and drive forward, if necessary, to avoid an obstacle. If the density of hazards in the terrain was too high to permit the vehicle to maintain a clear turning circle, a "thread the needle" approach could be enabled. This technique permitted the rover to drive between obstacles that were apart at least a vehicle's width. If enabled, the rover would attempt to drive in a straight line along the perpendicular bisector between the two obstacles. It would continue driving until it found a clearing large enough to turn around in before a specified distance was elapsed. If no such clearing was detected, it backed straight out to the point at which the "thread the needle" was initiated. Another direction for driving would then be attempted.

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Acknowledgement

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